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Enclosure 3

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The proliferation of wireless technology and the increasing demand for wireless data services have led to a re-examination of wireless network design, particularly with respect to optimal resource allocation. In a wireless ad-hoc environment, the lack of infrastructure, the need to perform resource allocation in a distributed fashion, and the time-varying nature of the network makes proposing an optimal design a difficult task. In this paper, we examine ad-hoc wireless networks in the context of variable-rate TCDMA (time and code division multiple access). We formulate this as a joint time-slot/rate assignment optimization problem, and present a simple algorithm that, while not producing an optimal result, is guaranteed to produce a feasible time-slot/rate assignment. This algorithm results in a self-configurable system with fault recovery capability.

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Joint Scheduling and Rate Control for Self-Configuring Ad-Hoc CDMA Networks

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Abstract

The proliferation of wireless technology and the increasing demand for wireless data services have led to a re-examination of wireless network design, particularly with respect to optimal resource allocation. In a wireless ad-hoc environment, the lack of infrastructure, the need to perform resource allocation in a distributed fashion, and the time-varying nature of the network makes proposing an optimal design a difficult task. In this paper, we examine ad-hoc wireless networks in the context of variable-rate TCDMA (time and code division multiple access). We formulate this as a joint time-slot/rate assignment optimization problem, and present a simple algorithm that, while not producing an optimal result, is guaranteed to produce a feasible time-slot/rate assignment. This algorithm results in a self-configurable system with fault recovery capability.

1 Introduction

The proliferation of wireless technology has led to an increased interest in the design of wireless ad-hoc networks. Such networks are characterized not only by the nature of the medium, but by the lack of infrastructure available for centralized computation. Mobiles must therefore use locally available information in order to *self-configure* a feasible network structure while trying to maximize the network throughput. However, practical issues regarding both the self-configurability of such networks, and the physical reality of the mobile radios, remain. For example, without the existence of software radios or multiple radio units, a node cannot receive and transmit simultaneously. This is the philosophy behind uplink/downlink division in a CDMA cellular system. In an ad-hoc environment with a flat architecture, however, such a time division becomes non-trivial.

We thus choose to examine ad-hoc networks in the context of TCDMA (time and code division multiple access) [7], in which CDMA is used as a multiple access scheme within individual time-slots. This is similar to the work done in [5] and [7]. However, the lack of scheduling requirements and the notion of wireless connections as links with variable capacity (using a general notion of information-theoretic capacity) in [5] leaves practical implementation unaddressed. The authors in [7] assume a fixed slot assignment scheme, but leave the construction of such a scheme unaddressed. Additionally, the authors in [7] focus on minimizing the transmit power of the mobiles, while we choose to maximize the transmission capacity of the network.

One of the biggest concerns in ad-hoc networks is connectivity - every node should be able to reach every other node through some routing scheme. Maintaining connectivity becomes even harder when considering wireless networks, and in particular *mobile* wireless networks. Several works (see [9], [11], [16], [19]) have examined the conditions required for connectivity in terms of topological distribution, transmission power, and the number of direct neighbors. Understanding the assumptions and conclusions of these papers will be important in designing an appropriate network scheme. Additionally, there is a large body of work on computing the capacity of ad-hoc networks ([3], [10], [17], [20], [21], [22]). Although these results are not extended to distributed systems, they are useful as an analytic tool for comparing the performance of our algorithm. It is important to note that the notion of capacity can be dependent upon the context in which it is examined. While [10], [20], and [22] define capacity in terms of the amount of information transmitted from source to destination, we choose to examine MAC-layer capacity, similar to [3]. In other words, we examine the transmission rate of each node without distinguishing between source and forwarded traffic. This scenario is especially applicable for networks where the majority of traffic at each node is intended for the node's nearest neighbors, e.g. smart home networking.

The remainder of this paper is organized as follows. Section 2 introduces the system model and some basic notation. Section 3 defines the feasible region of rate/slot assignments, and introduces the joint optimization problem. Section 4 presents a simple distributed algorithm that ensures feasibility but does not necessarily guarantee optimality. Section 5 addresses the performance of this algorithm by demonstrating convergence and stability. In addition, we show that this algorithm demonstrates both fault-recovery and self-configurability. This section also presents simulation results that demonstrate the performance of this algorithm. Finally, Section 6 provides conclusions and areas of future work.

2 CDMA Interference Model and Notation

We consider the following setting: there are a total of M mobiles and T transmission slots. We assume that for each user i there exists a time slot $s_i \in \{1, \ldots, T\}$, and a transmission rate r_i expressed in multiples of the fixed pilot rate, R_b (i.e. $r_i = R_b\alpha_i$). The channel gain from mobile i to mobile j is denoted by g_{ij}. W is the chip bandwidth, and N_0 is the thermal noise density. Note that $0 \leq R_b\alpha_i \leq W$. Mobiles are assumed to be receiving when they are not transmitting. Each mobile has a pilot power P_0^i, and transmission power $P_i = P_0^i\alpha_i$. The indicator function

$$\rho_{it} = \begin{cases} 1 & \text{if } s_i = t \\ 0 & \text{else} \end{cases}$$

is used to identify a given user's time-slot.

Definition 1. *The received pilot power of node i at node j can be written as*

$$\beta_{ij} = \begin{cases} P_0^i g_{ij} & \text{if } i \neq j \\ 0 & \text{else} \end{cases}$$

Definition 2. *The neighborhood of node i can be written as*

$$N_i = \left\{ j : SNR^j(i) \geq \gamma_0 \right\}$$

where $SNR^j(i) = \left(\frac{W}{R_b}\right)\frac{P_0^i g_{ij}}{N_0 W} = \frac{\beta_{ij}}{R_b N_0}$ is the signal to noise ratio for user i's pilot signal at node j in the absence of other transmissions.

Note that γ_0 should be chosen large enough so that the condition

$$SNR^j(i) \geq \gamma_0 \tag{1}$$

not only guarantees an acceptable bit error rate for user i's pilot signal, but will also guarantee an acceptable bit error rate for user $i's$ data stream in the presence of interference.

Definition 3. *The rise over thermal (ROT) is defined as*

$$Z_j(t) = \sum_{i=1}^{M} \frac{P_i g_{ij} \rho_{it}}{N_0 W}$$

and indicates the ratio of the total power received at mobile j over the thermal noise during time slot t [1].

Note that $Z_j(t)$ not only depends on how many neighbors are transmitting simultaneously, but also with what rate they are transmitting.

3 Problem Formulation

Definition 4. *A tuple of pilot power, time-slot and rate assignment vectors $(\underline{P_0}, \underline{s}, \underline{\alpha})$ belongs to the feasible region Δ if and only if they satisfy the following conditions:*

C1. $\nexists j \in N_i$ *such that* $s_i = s_j$

C2. $|N_i| \geq X \; \forall i$

C3. $Z_j(t) \leq K \; \forall j, t$

Condition C1 comes from the constraint that a node cannot transmit and receive at the same time. Condition C2 is believed to provide network connectivity with an appropriate choice of the value X. This has been shown to be on the order of 6 for networks with a uniformly distributed topology [16]. Condition C3, combined with Equation 1, implies that the signal-to-interference ratio satisfies $SINR^j(i) \geq \frac{\gamma_0}{1+K}$ [12]. The definition of N_i attempts to keep the SNR (excluding interference) of user i's pilot signal at a neighbor about γ_0. This, along with appropriate choices K, intuitively guarantees an acceptable $SINR$ in the presence of interference from other users.

Ultimately, we seek to maximize an appropriate objective function over the feasibility region. We assume that the objective function is of a social welfare form, i.e. it is of the form $\sum_{i=1}^{M} U(R_b \alpha_i)$ [2], where $U(\cdot)$ summarizes the value of rate increase for each mobile. Note that, since the maximum overall throughput might be achieved at the cost of specific users, the choice of $U(\cdot)$ represents the inherent trade-off between fairness and maximum possible throughput [15]. We focus on cases where $U(R_b \alpha_i)$ is monotone increasing and strictly concave.

For a given utility function $U(\cdot)$, a tuple of pilot power, time-slot, and rate assignment vectors is optimal if it is the solution to the following problem:

P. Find the pilot power, slot, and rate assignment vectors $(\underline{P_0}, \underline{s}, \underline{\alpha})$ that solve the following:

$$\max_{(\underline{P_0}, \underline{s}, \underline{\alpha}) \in \Delta} \sum_{i=1}^{M} U(R_b \alpha_i)$$

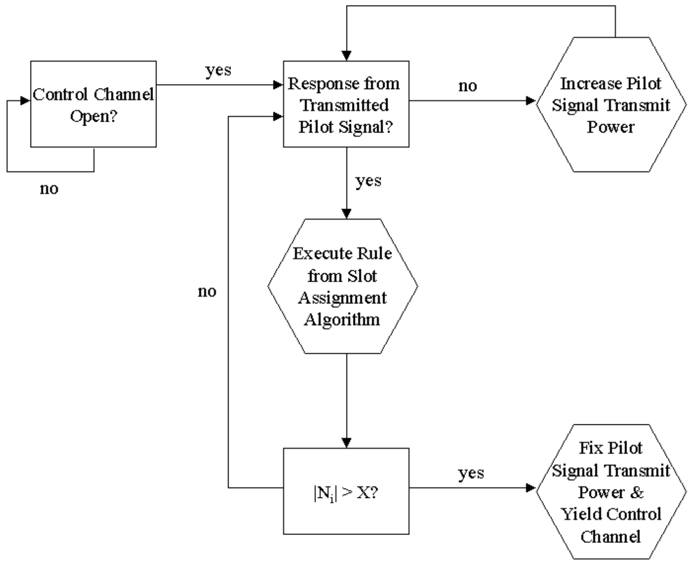

Figure 1: Flowchart of the Time Slot and Neighbor Discovery Algorithm

4 Distributed Algorithms

We formulate the problem described in Section 3 as a joint time-slot/rate assignment problem. Conceptually, this can be viewed as a generalization of the graph coloring problem where each node is assigned both a color (time-slot) and a height (rate). This interpretation admits a large body of work ([4], [8], [13], [14]). However, these works generally assume coloring is done on a graph with pre-defined links; in contrast, we propose to integrate neighbor discovery and graph coloring. Due to the complexity of finding a fully distributed solution, we propose to decompose this problem into the following alternate problems:

AP1. Find a set of pilot power and slot assignment vectors $(\underline{P_0}, \underline{s})$ that satisfy Conditions C1 and C2. (This results in a node-colored graph).

AP2. For a given vector of pilot power and slot assignments, find a vector of rate assignments $(\alpha_1, \ldots, \alpha_M)$ such that Condition C3 is satisfied, and that maximizes

$$\sum_{i=1}^{M} U(R_b \alpha_i) \tag{2}$$

Although this decomposition results in a generally sub-optimal solution, such a trade-off seems, at times, unavoidable to obtain a decentralized solution.

4.1 Neighbor Discovery / Time Slot Assignment Algorithm

In order to find a distributed solution to AP1, we combine the tasks of neighbor discovery and slot-assignment. In other words, each node starts with no neighbors and a randomly chosen time-slot assignment. The algorithm is then run one node at a time. This requirement is enforced by using random access on a separate control channel as a regulating mechanism. Once a node gains access to the control channel, it implements the following algorithm, shown in Figure 1:

1. Increment the pilot power until Eqn. (1) is satisfied at another node.

2. Choose a slot assignment using the rules in Figure 2.

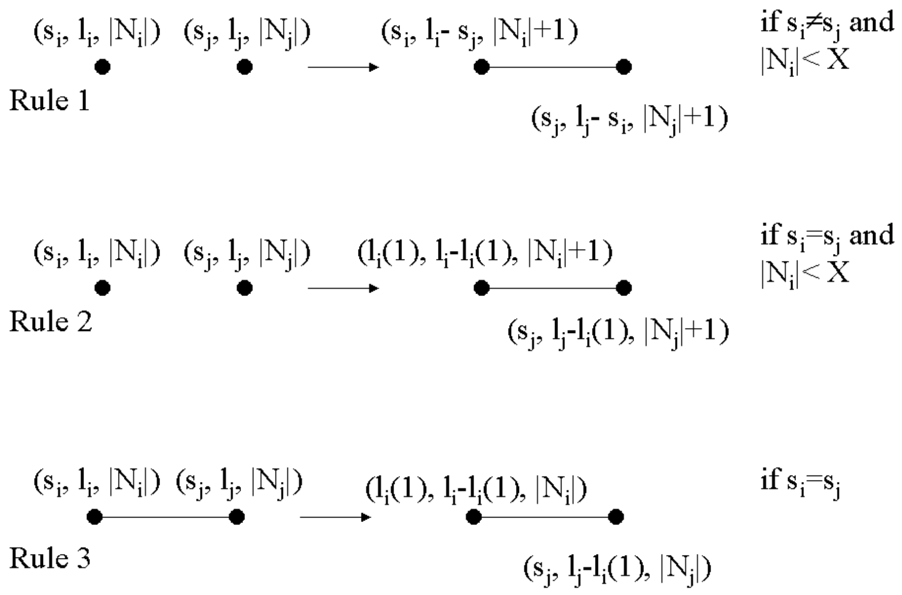

Figure 2: Slot Assignment Rules

3. Repeat until $|N_i| \geq X$.

In order to execute the rules shown in Figure 2, each node has three pieces of information: its own slot assignment (s_i), a list of the available slots not currently allocated to itself or its neighbors (l_i), and its number of neighbors ($|N_i|$). The configurations on the left show initial scenarios, while the configurations on the right show the scenarios after the execution of a rule. The text on the far right indicates the conditions under which a rule may be executed. Rules 1 and 2 allow a node to choose a slot based on its neighbor's slot. The existence of an available slot is guaranteed by the use of $T \geq X + 1$ slots [8]. Rule 3 ensures that any non-allowable links (established through initial configuration or system fault) are fixed.

It is important to note that this algorithm requires each node to accept and reciprocate all neighbor requests, regardless of its current number of neighbors. The result is that, although each node will only choose X neighbors for itself, some nodes may end the algorithm with more than X neighbors. In addition, it should be noted that there is a distinction between the neighborhood defined in Section 2, and the interference neighborhood. In other words, it is possible that nodes not in your neighborhood could still be close enough to cause significant interference. In closely dense networks, the interference from non-neighbors could result in a rate assignment of '0' as the only feasible transmission rate assignment. However, in practical settings and with an appropriate choice of X, this scenario does not represent a critical problem.

4.2 Rate Assignment Algorithm

Once neighbor discovery and slot assignment are complete, we can address the rate assignment problem as if the pilot powers and time-slots were fixed. This decouples the slot and rate assignment problems. Note that the time slotting allows the rate assignments during different time-slots to be decoupled from one another as well.

The authors in [12], [18] introduce a distributed algorithm for rate control in cellular CDMA systems. Once the neighbor discovery and time-slot assignments are fixed, it

is straightforward to extend this work to the ad-hoc scenario described in this paper. During a given time-slot, each receiving node acts like a base, monitoring its interference level and broadcasting a price based on that interference level. Each mobile assigned to transmit then reacts to these prices by increasing or decreasing its rate. As previously mentioned, the choice of $U(\cdot)$ captures the trade-off between throughput and fairness. Here, we focus on a proportional fair solution, shown to be achieved by using the utility function $U(\cdot) = \log(\cdot)$ [15].

The algorithms developed in [12] and [18] consist of two parts, and are applied to the ad-hoc scenario as follows:

1. Receiving mobiles broadcast a vector of signals indicating their observed level of interference for each time slot. These signals evolve according to the following difference equation:

$$\Delta\mu_j(t) = \xi[Z_j(t) - K]^+ \tag{3}$$

where $\mu_j(t) = 0$ if $\rho_{jt} = 1$, and ξ is a constant.

2. Transmitting mobiles use these signals to adjust their rates as follows:

$$\alpha_i = \arg\max_{\alpha}(\log(R_b\alpha) - \alpha\sum_{t=1}^{N} p_i\rho_{it}) \tag{4}$$

where $p_i = \sum_{j=1}^{M} \mu_j(t)\beta_{ij}$.

5 Algorithm Performance

In this section, we examine the convergence and stability of the algorithms developed in Section 4. In addition, we examine the algorithm performance through numerical examples and simulations.

5.1 Convergence and Stability

A self-stabilizing system is one in which the system is guaranteed to reach a feasible state from any initial condition after a finite number of operations [6]. This also implies that if system faults are spaced far enough apart, the system has fault-recovery ability. We show that, even when run simultaneously, the neighbor discovery/time-slot assignment and rate assignment algorithms presented in Section 4 are self-stabilizing systems. To do so, we introduce the following lemmas and theorems:

Lemma 1. *An equilibrium point of neighbor discovery and time-slot selection is stable and solves AP1 if Rules (1)-(3) are executed one at a time.*

Proof. We first introduce the following Lyapunov-type function:

$$\varphi_S = \sum_{i=1}^{M}[X - |N_i|]^+ + \sum_{t=1}^{T}[\sum_{i=1}^{M}\sum_{j=1}^{M}\rho_{it}\rho_{jt}\psi_{ij}] \tag{5}$$

where $[x]^+ = 0$ if $x < 0$ and ψ_{ij} is an indicator function used to tell if i and j are neighbors. This is a non-negative function which decreases with every application of a rule from Figure 2. Rules 1 and 2 decrease the first term and do not affect the second, since they only create valid links when one of the involved nodes has less than X neighbors. Rule 3 decreases the second term, and does not affect the first term since it only fixes faulty links. The condition $\varphi_S = 0$ represents a feasible slot assignment, since it means that

every node has at least X neighbors and all neighbors transmit during different slots. This also represents a stable state, since no rules can be executed when $\varphi_S = 0$. Thus we can conclude that the algorithm will converge to a stable, feasible slot assignment in a finite number of steps from any initial state. □

Lemma 2. *Given a set of pilot power and time-slot assignment vectors, an equilibrium point of the distributed system described by Eqns (3)-(4) solves AP2.*

Proof. We assume that we wish to maximize the sum of the utility functions. Now, consider the Lagrangian:

$$\begin{aligned}\mathcal{L}(\underline{\alpha}, \underline{\mu}) &= \sum_{i=1}^{M} \log(R_b \alpha_i) \\ &- \sum_{t=1}^{T} \sum_{j=1}^{M} \mu_j(t) \left(\sum_{i=1}^{M} \frac{\alpha_i \beta_{ij} \rho_{it}}{N_0 W} - K \right) \\ &= \sum_{i=1}^{M} \left(\log(R_b \alpha_i) - \alpha_i \sum_{t=1}^{T} \sum_{j=1}^{M} \frac{\beta_{ij} \rho_{it} \mu_j(t)}{N_O W} \right) \\ &+ K \sum_{j=1}^{M_{RCV}} \mu_j\end{aligned}$$

The dual problem can be formulated as follows:

DP. Find the Lagrangian multipliers $\mu_j(t)$ such that they solve

$$min_{\underline{\mu} \geq 0} \sum_{i=1}^{M} \phi_i(p_i) + K N_0 W \sum_{t=1}^{T} \sum_{j=1}^{M} \mu_j(t)$$

where $p_i = \sum_{j=1}^{M} P_0^i g_{ij} \rho_{it} \mu_j(t)$
and $\phi_i(p_i) = max_{\alpha_i} \left(\log(R_b \alpha_i) - \alpha_i p_i \right)$

The rate assignment algorithm is derived from this dual problem. The rate assignment described by Eqn (4) is simply the solution to $\phi_i(p_i)$ for a given set of Lagrangian multipliers, $\underline{\mu}$. The price updates described by Eqn (3) are simply a gradient projection method to compute the Lagrangian multipliers. The linearity of the constraint $Z_j(t) \leq K$ combined with a strictly increasing and concave utility function implies that this algorithm will converge to the equilibrium point in a finite amount of time (see [12], [18]). □

Using these lemmas, we introduce the following theorem:

Theorem 1. *Rules (1)-(3) and Equations (3)-(4) represent a self-stabilizing system whose equilibrium point solves AP1 and AP2 if Rules (1)-(3) are executed one at a time.*

Proof. Rules (1)-(3) are not dependent upon the rate assignment vectors. Although Eqns (3)-(4) are dependent upon the pilot powers and slot assignments, we know that after a finite amount of time Rules (1)-(3) can no longer be executed and the slot assignments are fixed. At this point, Lemma 2 holds true. Thus, the slot and rate assignment algorithms can be run simultaneously, and will still converge to a stable equilibrium point in a finite number of steps. □

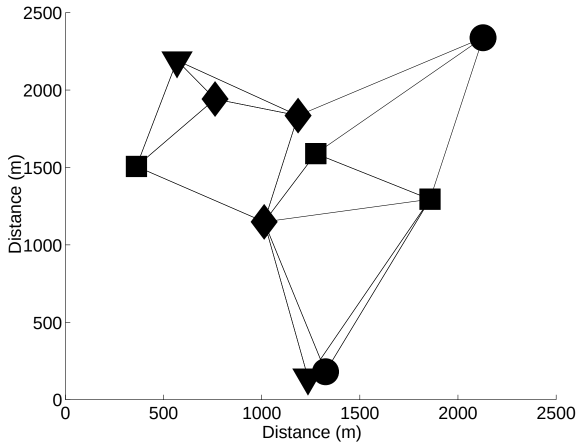

Figure 3: Faulty Slot and Neighbor Assignments for a Subset of 10 Mobiles

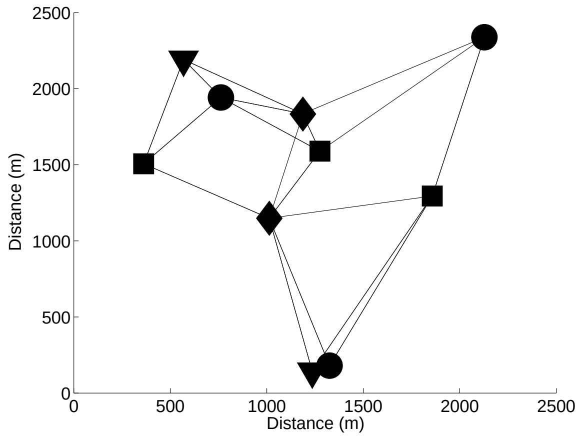

Figure 4: Final Slot and Neighbor Assignments for a Subset of 10 Mobiles

5.2 Simulation Results

Simulations were run using a network of 50 nodes randomly distributed over a 2500m x 2500m grid. The simulations use a cost-231 propagation model at 1.9 GHz between the mobiles. The values for γ_0 and K are 4dB and 10dB respectively. The chip bandwidth W is 1.2 MHz, the thermal noise density N_0 is -179 dBm/Hz, and the pilot rate R_b is 4.8 Kbps. The values for X and T are 6 and 7, respectively. The initial choices for slot and rate assignments were chosen at random.

The slot assignment algorithm was run on a random node at each iteration. In other words, the actual random access of the control channel was approximated by simply selecting random nodes one at a time. Figure 3 shows a faulty network configuration (i.e. some nodes are transmitting in the same slot as their neighbors, or have too few neighbors) for a 10-mobile subset of the network. Figure 4 shows the final network configuration for the same subset after the neighbor discovery/time-slot assignment algorithm has been run. The links in which neighbors had the same slot assignment have been fixed, and all nodes have enough neighbors.

The rate assignment algorithm was run for a single time-slot at each iteration. Figure 5 shows the number of infeasible links at each iteration. We can see that this function is decreasing and stabilizes at '0'. Finally, Figure 6 shows the system throughput using a strict threshold model, in which a given mobile is assumed to have perfect reception if Condition C3 is satisfied, and no reception if it is violated.

6 Conclusions

The most important factor in designing self-configurable ad-hoc networks is that the algorithms must work in a distributed manner. In this paper, we establish conditions for feasible ad-hoc CDMA network configurations, and introduce a joint time-slot/rate assignment optimization problem based on those conditions. By decoupling the time-slot and rate assignment problems, we have implemented algorithms that ensure feasible allocations but do not necessarily address optimality. The slot assignment algorithm presented in this paper, while ensuring a feasible assignment, is overly conservative. Distributed node coloring algorithms are known to be inefficient; therefore, the optimality of the slot assignment algorithm could be improved by assigning multiple slots to a single user, or using auctioning mechanisms to aid in slot assignment.

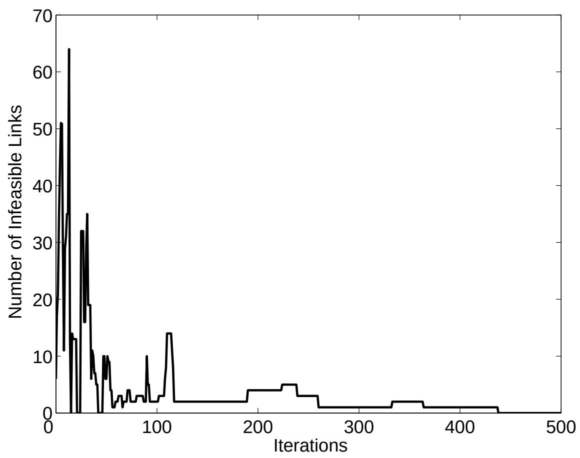

Figure 5: Number of Infeasible Links in the Network

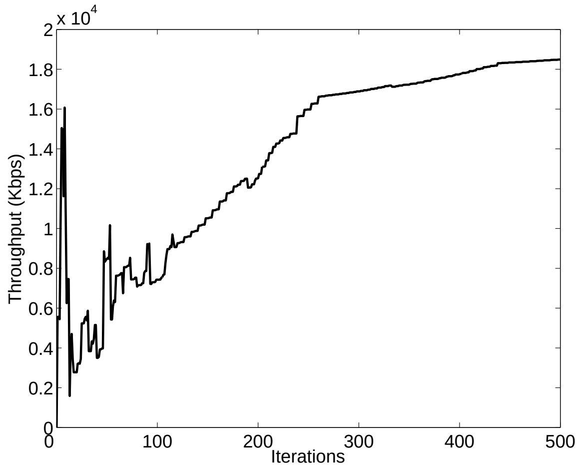

Figure 6: System Throughput Using a Perfect Reception Interference Threshold K

In addition, the interaction of routing with these algorithms will have a significant impact on system performance. Evaluating this impact and exploring cross-layer techniques that incorporate routing information into the slot and rate assignment algorithms is an important area of future work. Finally, comparing the performance of these algorithms to known upper bounds on network capacity will allow for a more rigorous evaluation of the algorithm performance. The key to any future work will be to continue to implement network configuration in a distributed manner.

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